

Direct CP Violation in Nonleptonic Charm Decays¹

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LHCb, CDF and most recently Belle have observed a large difference between direct CP asymmetries in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$. We use the measured value of ΔA_{CP} to constrain the magnitude and strong phase of a QCD-enhanced standard model penguin and predict its effects on direct CP asymmetry in $D^0 \rightarrow \pi^0\pi^0$ and $D^+ \rightarrow K^+\bar{K}^0$.

The LHCb and CDF Collaborations have reported evidence for close to a percent-level CP violation [1] in the difference between direct CP asymmetries (ΔA_{CP}) in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$. Their result has very recently been corroborated by the Belle Collaboration [2]. The conventional standard model (SM) prediction for ΔA_{CP} , however, is at least an order of magnitude smaller due to Cabibbo-Kobayashi-Maskawa (CKM) suppression. The deviation of the measured ΔA_{CP} from its SM prediction has naturally led to the discussion of whether this is a new signature of physics beyond the SM. However, the closeness of the charm-quark mass (m_c) to the scale at which perturbative QCD breaks down (Λ_{QCD}) presents an opportunity to rescue SM physics. The hope is that non-perturbative QCD contributions can generate enough enhancement to compensate for the large CKM suppression.

Although it is quite early to conclude whether or not this is new physics, a useful exercise is to constrain the SM parameters using these measurements and to predict their effects on other D -meson decays where CP-asymmetries are yet to be measured. In this talk, we present our analysis of D meson decay rates and CP asymmetries based on flavor-SU(3) symmetry. We assume that an enhanced SM $c \rightarrow b \rightarrow u$ penguin is responsible for the large measured ΔA_{CP} and we quantify its effects on direct CP asymmetry in $D^0 \rightarrow \pi^0\pi^0$ and $D^+ \rightarrow \bar{K}^0 K^+$. The analysis presented in this talk closely follows that in Ref. [3], with the addition of new updates from a Belle preliminary analysis [2].

D meson decays to two pseudoscalar mesons were studied in Ref. [4]. D decays are of three kinds: a) Cabibbo-favored (CF) (proportional to $V_{cs}^*V_{ud}$), b) singly-Cabibbo-suppressed (SCS) (proportional to $V_{cd}^*V_{ud}$ or $V_{cs}^*V_{us}$) and c) doubly-Cabibbo-suppressed (DCS) (proportional to $V_{cd}^*V_{us}$). Since the CF and DCS transitions involve

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distinct quark flavors, these amplitudes don't get penguin contributions. In Ref. [4] it was shown that flavor-SU(3) symmetry using tree-level topologies T , C , E and A is able to fit the measured CF decay amplitudes with good precision. Under flavor-SU(3) symmetry the SCS decay amplitudes for $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ are expected to obey:

$$\mathcal{A}(D^0 \rightarrow K^+K^-) = -\mathcal{A}(D^0 \rightarrow \pi^+\pi^-) = \lambda(T + E) , \quad (1)$$

where $\lambda = \tan \theta_{\text{Cabibbo}} = 0.2317$. Also the amplitude for $D^0 \rightarrow K^0\bar{K}^0$ is expected to vanish. In practice, however, the measured amplitude for $D^0 \rightarrow K^0\bar{K}^0$ is found to be 239 ± 14 eV while that for $D^0 \rightarrow \pi^+\pi^-(K^+K^-)$ is found to be smaller (larger) than the corresponding flavor-SU(3) prediction.

Factorizable flavor-SU(3) breaking effects in the amplitude T can be calculated in terms of meson masses (m_K , m_π) and decay constants (f_K , f_π):

$$T_\pi = T \cdot \frac{|f_{+(D^0 \rightarrow \pi^-)}(m_\pi^2)|}{|f_{+(D^0 \rightarrow K^-)}(m_\pi^2)|} \cdot \frac{m_D^2 - m_\pi^2}{m_D^2 - m_K^2} , \quad (2)$$

$$T_K = T \cdot \frac{|f_{+(D^0 \rightarrow K^-)}(m_K^2)|}{|f_{+(D^0 \rightarrow K^-)}(m_\pi^2)|} \cdot \frac{f_K}{f_\pi} . \quad (3)$$

These corrections diminish the discrepancy between theory and measured amplitudes, but they are not enough. Furthermore, factorizable corrections do not affect the amplitude for $D^0 \rightarrow K^0\bar{K}^0$. We recall that the SCS decay amplitudes can get contributions from penguin topologies which are ordinarily suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism, but which may be nonzero if flavor SU(3) is broken. Once these penguins are included we have additional parameters that may be extracted from the data as shown in Ref. [3]. In Table 1 we present the flavor-topology representations for the SCS D decays to pions and kaons, alongside the theory fit and measured amplitudes. We have also listed the overall strong phase (ϕ_T^f) for each process.

The tiny weak-phase difference between the tree-level amplitudes and the GIM-suppressed penguins P and PA is insufficient to produce a ΔA_{CP} as large as measured by LHCb, CDF and Belle. The measured ΔA_{CP} calls for an enhanced $c \rightarrow b \rightarrow u$ penguin denoted by P_b ². Let us parameterize the CP-conserving part of an SCS amplitude as $T_f = |T_f|e^{i\phi_T^f}$ and the CP-violating penguin part as $P_b = p e^{i(\delta-\gamma)}$, where δ and γ are respectively its strong and weak phases. We use $\gamma = 76^\circ$. The amplitude for a general SCS D decay to a final state f is

$$\mathcal{A}(D \rightarrow f) = T_f + P_b = |T_f|e^{i\phi_T^f} \left(1 + \frac{p}{|T_f|} e^{i(\delta-\phi_T^f-\gamma)} \right) . \quad (4)$$

²Note that both P, PA and P_b require the same enhancement as explained in detail in Ref. [3]

Table 1: Representations and comparison of experimental and fit amplitudes for SCS decays of charmed mesons to two pseudoscalar mesons. Also listed is the overall strong phase (ϕ_T^f) for each process [3].

Decay Mode	Amplitude representation	$ \mathcal{A} $ (10^{-7} GeV)		ϕ_T^f degrees
		Experiment	Theory	
$D^0 \rightarrow \pi^+\pi^-$	$-\lambda(T_\pi + E) + (P + PA)$	4.70 ± 0.08	4.70	-158.5
$D^0 \rightarrow K^+K^-$	$\lambda(T_K + E) + (P + PA)$	8.49 ± 0.10	8.48	32.5
$D^0 \rightarrow \pi^0\pi^0$	$-\lambda(C - E)/\sqrt{2} - (P + PA)/\sqrt{2}$	3.51 ± 0.11	3.51	60.0
$D^+ \rightarrow \pi^+\pi^0$	$-\lambda(T_\pi + C)/\sqrt{2}$	2.66 ± 0.07	2.26	126.3
$D^0 \rightarrow K^0\bar{K}^0$	$-(P + PA) + P$	2.39 ± 0.14	2.37	-145.6
$D^+ \rightarrow K^+\bar{K}^0$	$\lambda(T_K - A_{D^+}) + P$	6.55 ± 0.12	6.87	-4.2
$D_s^+ \rightarrow \pi^+K^0$	$-\lambda(T_\pi - A) + P$	5.94 ± 0.32	7.96	174.3
$D_s^+ \rightarrow \pi^0K^+$	$-\lambda(C + A)/\sqrt{2} - P/\sqrt{2}$	2.94 ± 0.55	4.44	16.4

The amplitude for the CP-conjugate process $\bar{\mathcal{A}}(\bar{D} \rightarrow \bar{f})$ can be obtained by changing the sign of the weak phase γ in Eq. (4). The direct CP asymmetry in $D \rightarrow f$ can then be expressed as:

$$\begin{aligned}
A_{CP}(f) &= \frac{|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2} = \frac{2(p/|T_f|) \sin \gamma \sin(\delta - \phi_T^f)}{1 + (p/|T_f|)^2 + 2(p/|T_f|) \cos \gamma \cos(\delta - \phi_T^f)} \\
&\approx 2(p/|T_f|) \sin \gamma \sin(\delta - \phi_T^f) ,
\end{aligned} \tag{5}$$

The measured value of ΔA_{CP} from LHCb, and CDF [1] is

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.67 \pm 0.16)\% \tag{6}$$

We constrain p as a function of δ using Eq. (5) along with the measured value of ΔA_{CP} . In addition, we use the Belle preliminary results [2] as bounds for the individual CP asymmetries in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$:

$$A_{CP}(D^0 \rightarrow K^+K^-) = (-0.23 \pm 0.15)\% , \quad A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (0.27 \pm 0.20)\% , \tag{7}$$

from which we calculate the following 90% confidence-level limits:

$$-0.48\% \leq A_{CP}(K^+K^-) \leq 0.02\% , \quad -0.06\% \leq A_{CP}(\pi^+\pi^-) \leq 0.60\% . \tag{8}$$

These numbers put a bound on the range of allowed values of δ to $-2.59 \leq \delta \leq 0.39$. (The CP asymmetries are approximately invariant under the joint transformations $\phi_T^f \rightarrow -\phi_T^f$ and $\delta \rightarrow \pi - \delta$ as long as $p/|T_f|$ is small compared to unity.) In Fig. 1 we plot p as a function of δ within this allowed range. In this plot p stays close to 10^{-9} GeV for a large range of δ .

We now use the p - δ constraint to find its effects on the individual CP asymmetries $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$ as well as predict the CP asymmetries in $D^0 \rightarrow \pi^0\pi^0$

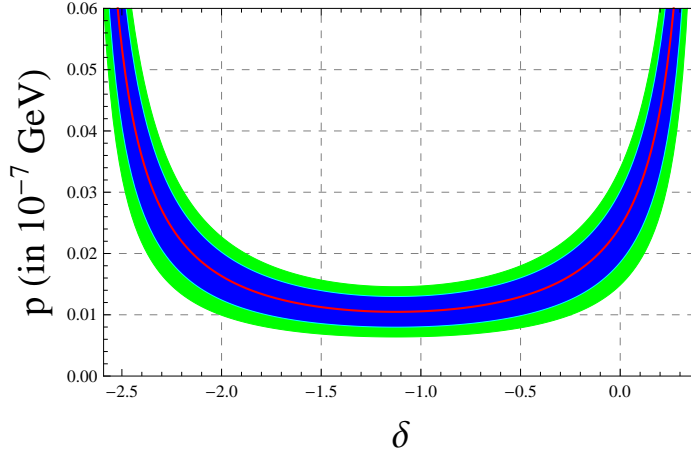


Figure 1: p and δ allowed by the measured range of ΔA_{CP} . The (red) line represents the central value, while inner (blue) and outer (green) bands respectively represent 68% (1σ) and 90% (1.64σ) confidence-level regions based on error in ΔA_{CP} .

and $D^+ \rightarrow K^+ \bar{K}^0$. In Fig. 2 we plot the individual CP asymmetries as a function of δ . The plots show that the direct CP asymmetries are correlated and that for a large range of δ , A_{CP} is positive (negative) for $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow \pi^0 \pi^0$ ($D^0 \rightarrow K^+ K^-$ and $D^+ \rightarrow K^+ \bar{K}^0$). Preliminary results from Belle, 2012 [2] indicate $A_{CP}(D^+ \rightarrow K^+ \bar{K}^0) = (0.082 \pm 0.275 \pm 0.135)\%$. The corresponding 90% confidence-level bounds are shown as red dashed lines in the lower right panel plot of Fig. 2. A large range of δ is still allowed by the measured CP asymmetries. In this talk, we have presented a model based on flavor topologies that accounts well for the measured decay rates in CF D decays. SU(3) breaking in SCS decays is taken care of by introducing the ordinarily GIM-suppressed penguin as a parameter. The LHCb, and CDF observed large difference in CP asymmetries between $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ is used to constrain the magnitude and strong phase of a $c \rightarrow b \rightarrow u$ penguin, which is then used to predict CP asymmetries in $D^0 \rightarrow \pi^0 \pi^0$ and $D^+ \rightarrow K^+ \bar{K}^0$. In our model we have neglected a CP-violating annihilation penguin, which may give rise to A_{CP} in $D^0 \rightarrow K^0 \bar{K}^0$. Under isospin symmetry the amplitude for $D^+ \rightarrow \pi^+ \pi^0$ doesn't involve penguins, and hence the associated direct CP asymmetry vanishes. Future measurements may make it possible to apply this analysis to D_s^+ decays as well as D decays to a pseudoscalar and a vector.

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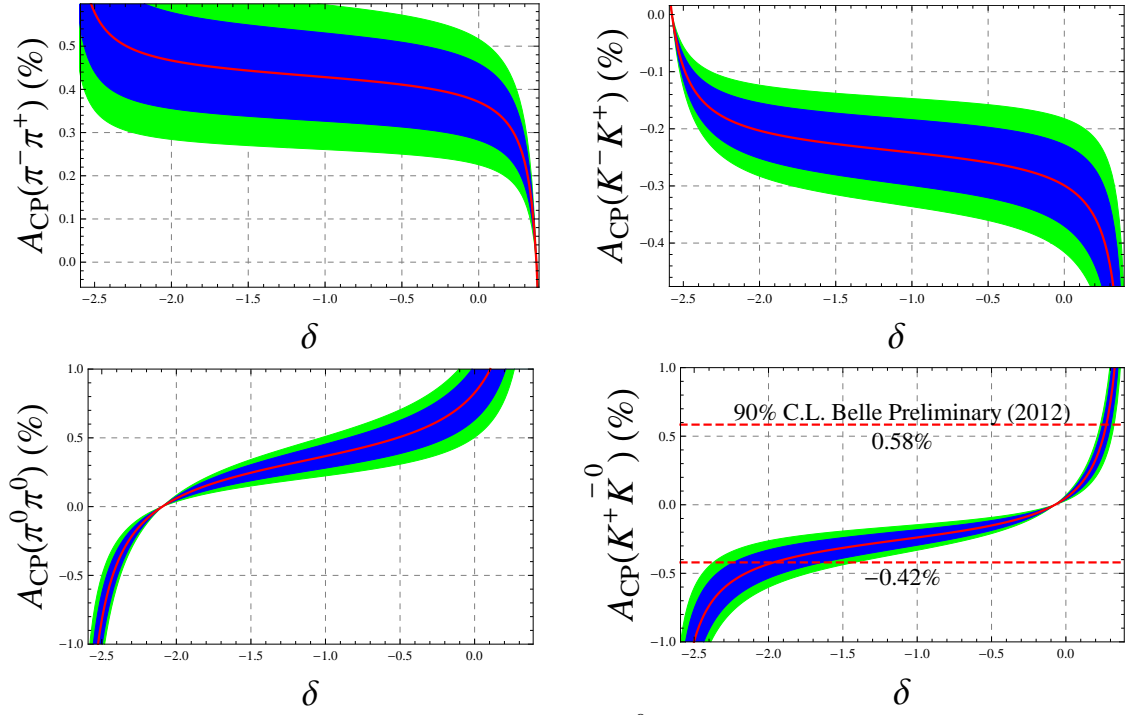


Figure 2: Direct CP asymmetry in various D^0 and D^+ decay modes plotted as a function of δ . The red dashed lines in the lower-right-hand plot shows 90% (1.64 σ) confidence-level preliminary bounds from Belle, 2012 [2]. The solid (red) lines represent the central values, while inner (blue) and outer (green) bands respectively represent 68% (1 σ) and 90% (1.64 σ) confidence-level regions based on error in ΔA_{CP} .

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